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Cold Regions Research and Engineering Laboratory

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Seismic-Acoustic Active Range Monitoring for Characterizing Low-Order Ordnance Detonation

Thomas S. Anderson and Jason C. Weale

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Prepared for U.S. Army Corps of Engineers

Abstract: A seismic-acoustic field data acquisition experiment was conducted in March 2005 to support the ERDC Environmental Quality program, Distributed Source focus area. The Distributed Sources focus area strives to characterize the level of contamination in range environments attributed to ordnance residue for the purpose of range management and environmental remediation. This remote sensing research project emphasizes seismic magnitude measurements and subsequent inference of partial detonations and unexploded ordnance. The analysis of these data will help establish seismic-acoustic measurement criteria for remotely sensed seismic data to enable near-real time estimates of the seismic source characteristics of ordnance explosions, including level of detonation and location. We collected seismic and acoustic array data from Yuma Proving Ground from 7 to 18 March 2005. Three sensor nodes were set up over approximately 16-km^2 areas that encompassed partial or full impact regions. We employed both seismic and acoustic arrays with accompanying meteorological stations. The dual mode of acoustic and seismic monitoring is seen to have great benefit in discerning acoustic arrival from the seismically propagated energies. Acoustic arrivals that are attributed to ordnance detonation or muzzle blast are observed on both the seismic sensors and microphones with an extremely high signal-to-noise ratio. The experimental data acquisition of March 2005 provided a catalogue of waveforms that help to define the seismic and acoustic phase energy observed at several kilometers for sensor offset and a source scale of artillery ordnance magnitude.

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Preface

This technical note was prepared by Dr. Thomas S. Anderson, Civil and Infrastructure Engineering Branch, and Jason C. Weale, Applied and Military Engineering Branch, U.S. Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory (CRREL), Hanover, NH.

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The authors thank David Fisk, Tom Hall, Doug Punt, John Fiori (all from CRREL) for their participation in the field program. Also thanked are Range Officers Ramon Noriega and Alan Tinseth of the Smart Weapons Test Range (SWTR) site for their extensive assistance during these tests.

This technical note was prepared under the general supervision of Dr. Justin Berman, Chief, Civil and Infrastructure Engineering Branch; Dr. Lance Hansen, Deputy Director; and James L. Wuebben, Acting Director, CRREL.

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1 Introduction

Environmental and safety issues on DoD training ranges associated with low-order detonations and unexploded ordnance (UXO) present an extremely difficult and expensive problem for DoD range managers. Current methods for locating and remediating such ordnance are extremely costly and imperfect, and they are also implemented after the fact, potentially creating a new contaminated range problem after every training exercise. To meet the requirement for sustained training operations, an effective capability must be devised to enable the cost-effective management and cleanup of ranges. Near-real-time detection, location, and characterization of ordnance using seismic and acoustic sensors may provide just such a capability. Developing and maintaining a database of the number of rounds fired, impact time, location, and level of detonation will provide an invaluable management tool for addressing singular low-order or UXO events and for devising fiscally optimal cleanup schedules and management criteria.

The U.S. Air Force has successfully used seismic and acoustic monitoring of the world's largest ordnance, nuclear bombs, for over 40 years, demonstrating that it is possible to develop a real-time remote sensing capability for processing over 3,000 seismic events in a day with minimal, but specialized, human oversight. Further, there is much from the nuclear monitoring mission that may be applied to the range monitoring problem, such as analysis software, analysis methods, and database schema. The problem is far from solved, though, and research is needed to understand the seismic and acoustic source and propagation phenomena at scales of meters to kilometers. Fundamental to developing this understanding is a well-documented and robust empirical data set to derive detection thresholds, local phase arrivals, information about ordnance source phenomena, and event association.

This report documents the data collection effort during the first year of an active range monitoring effort. This report includes a list of the records obtained during the tests, documentation of the sensor array, a table of sensors used, environmental characterization, and a description of data processing. Plots of example signatures are provided, representative of the data set that was archived in Center for Seismic Studies (CSS) format. An

analysis report documenting the data interpretation and describing the recorded data in greater detail is in preparation.

This research program contributes to both force protection and environmental quality by determining the source of fired rounds to assist with fire suppression and by locating impact points and characterizing detonation completeness of fired rounds to improve residue cleanup. Use of this and other data sets will assist the Army in its design of an artillery characterization system for cost-effective, long-term DoD range maintenance and sustainment.

2 Overview of Test

Seismic-acoustic signatures produced by artillery and artillery ordnance were recorded over a two-week period at the KOFA (King of Arizona) Artillery Test Range at Yuma Proving Ground (YPG), Yuma, AZ, from 7 through 18 March, 2005 (Fig.1). The KOFA test is an integrated facility for open-air testing of tanks, artillery, mortars, mines, and small missiles, with a firing range capability of up to 75 km. The range complex has 21 fixed, permanent firing positions and over 310 surveyed firing points and is highly utilized, e.g. in 1999 over 33,000 large-caliber rounds were expended, making it an excellent choice for monitoring and characterizing active ranges.

The March 2005 field data acquisition was the first field range monitoring and characterization effort in support of the active range monitoring research program in the Distributed Sources focus area. The field experiment was planned and executed with the purpose of characterizing the level of detonation and locating ordnance impacts. The goals of this test were:

- Determine the source of fired rounds,
- Locate impact points, and
- Characterize the completeness of detonations.

To accomplish these goals, we continuously recorded seismic, acoustic, and meteorological data and devised a database with meticulous meta information for subsequent analysis. To mitigate the high costs of range support over an extended period of time, we collected data from ongoing artillery operations. The data acquisition program was largely successful and has provided insight into the complexities of active range monitoring, potential benefits, and system requirements.

The first week of tests (7–14 March 2005) was conducted at the west end of YPG, with gun positions 2, 4, 8, and 12 firing to an impact area between 90 Degree Road and the 31,000-m N YPG grid line (Fig. 2). The second week of tests (15–18 March 2005) was conducted at the Extended HE Impact area from the same gun positions used during the first week (Fig. 3). Signatures were also recorded for the CRREL 10-gauge seismic calibrator that was used to further quantify the environmental effects on acoustic

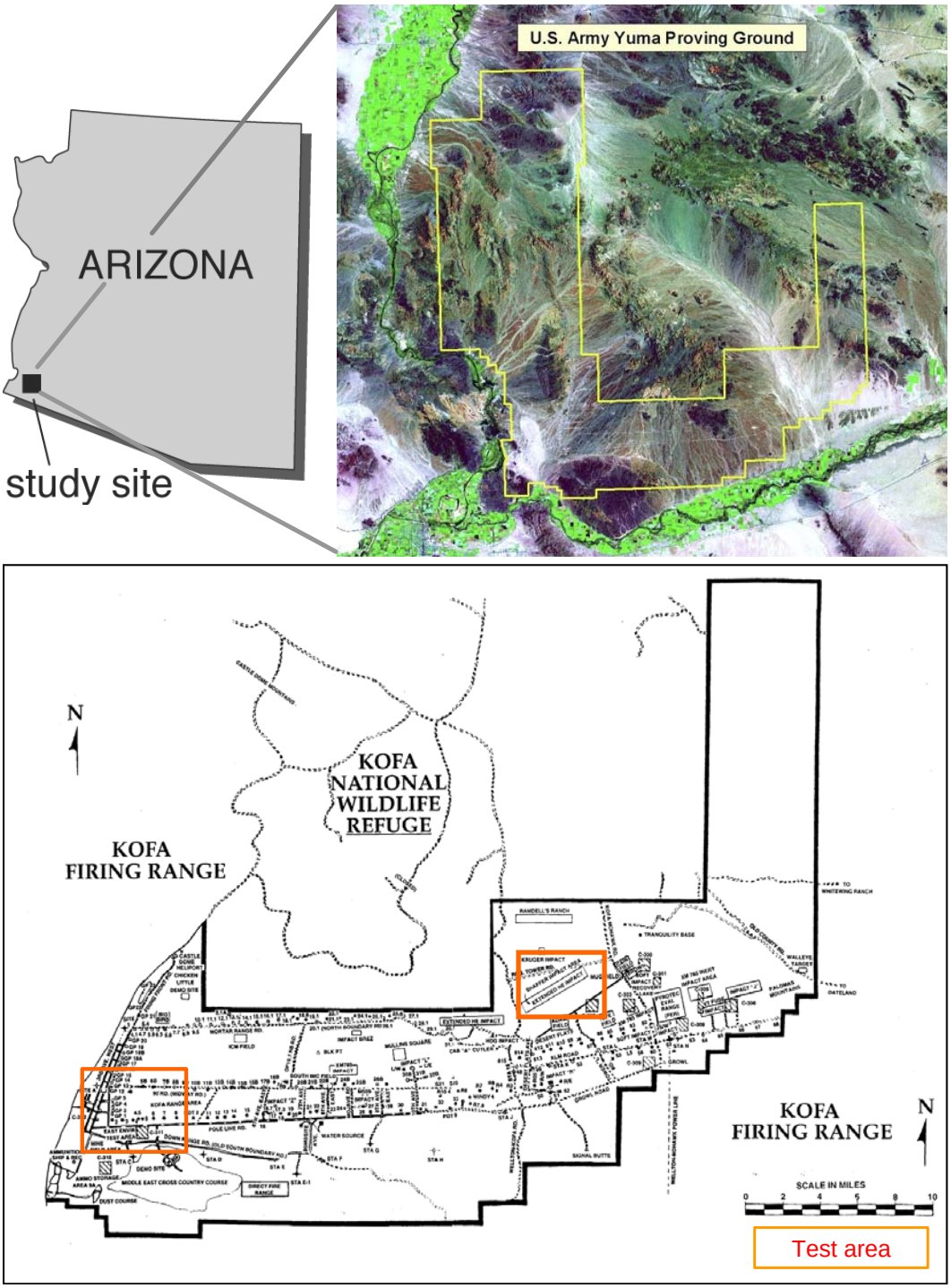


Figure 1. Yuma Proving Ground (YPG), AZ, test areas. The mortar fire from week 1 was in the western portion of the range (the orange box). The high-explosive artillery was monitored in the boxed region in the eastern part of the range.

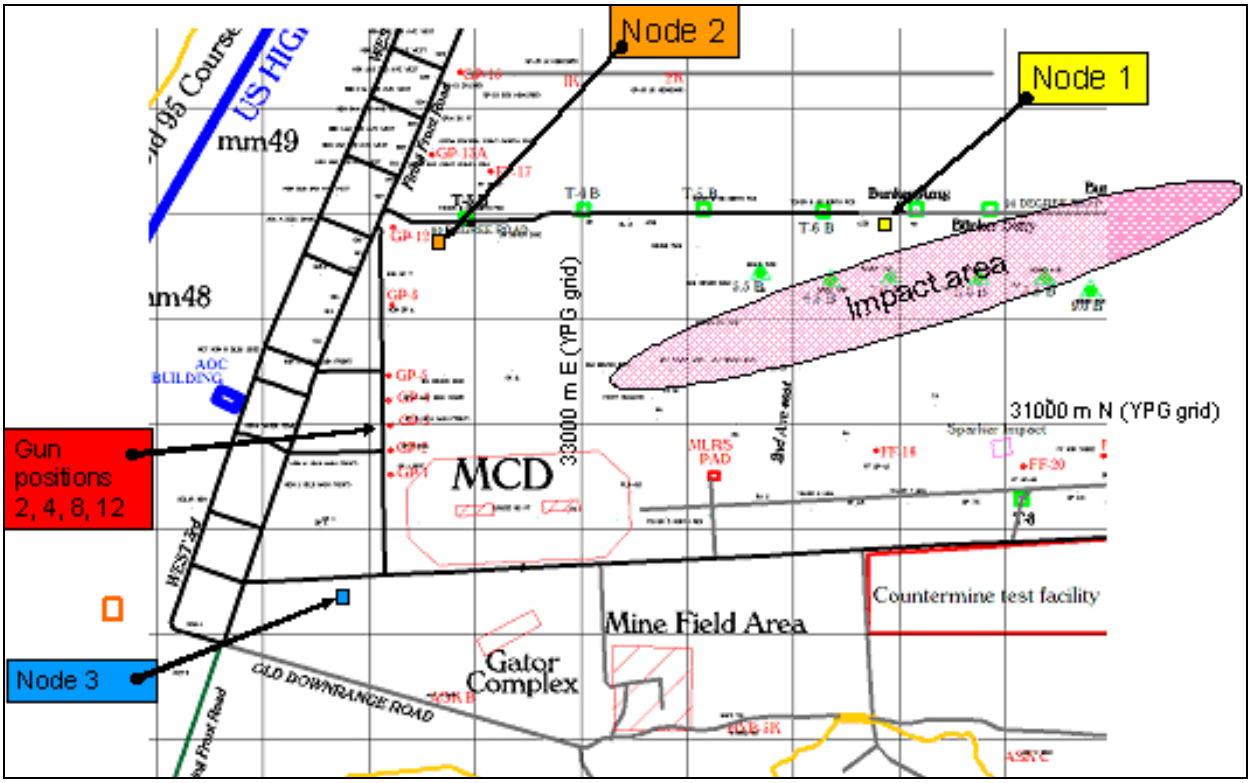


Figure 2. Detailed map (with 1-km grid lines) of the test area for week 1 (Fig, 1), depicting the gun firing positions, the impact area, and the data collection points (nodes).

properties and ground impedance at the test range. The following is a summary of our accomplishments:

- Approximately 700,000 1-s files were recorded (continuous daily records).
- Records were collected for more than 456 rounds fired on 7–10 March (primarily week 1).
- Records were collected for more than 90 rounds fired on 15–18 March (primarily week 2).
- 60-, 81-, and 120-mm mortars were recorded.
- 105- and 155-mm howitzers were recorded.
- Records were collected for 91 calibration shots (49 10-gauge and 42 propane cannon).

All of the mortar and howitzer rounds were fired during normal live-fire training exercises, and our data were collected as “targets of opportunity” during these events. Thus, we do not have a complete “matrix of tests” as during some of our previous efforts, but we were able to collect a large volume of data in a cost-effective manner under realistic firing scenarios at a very active range.

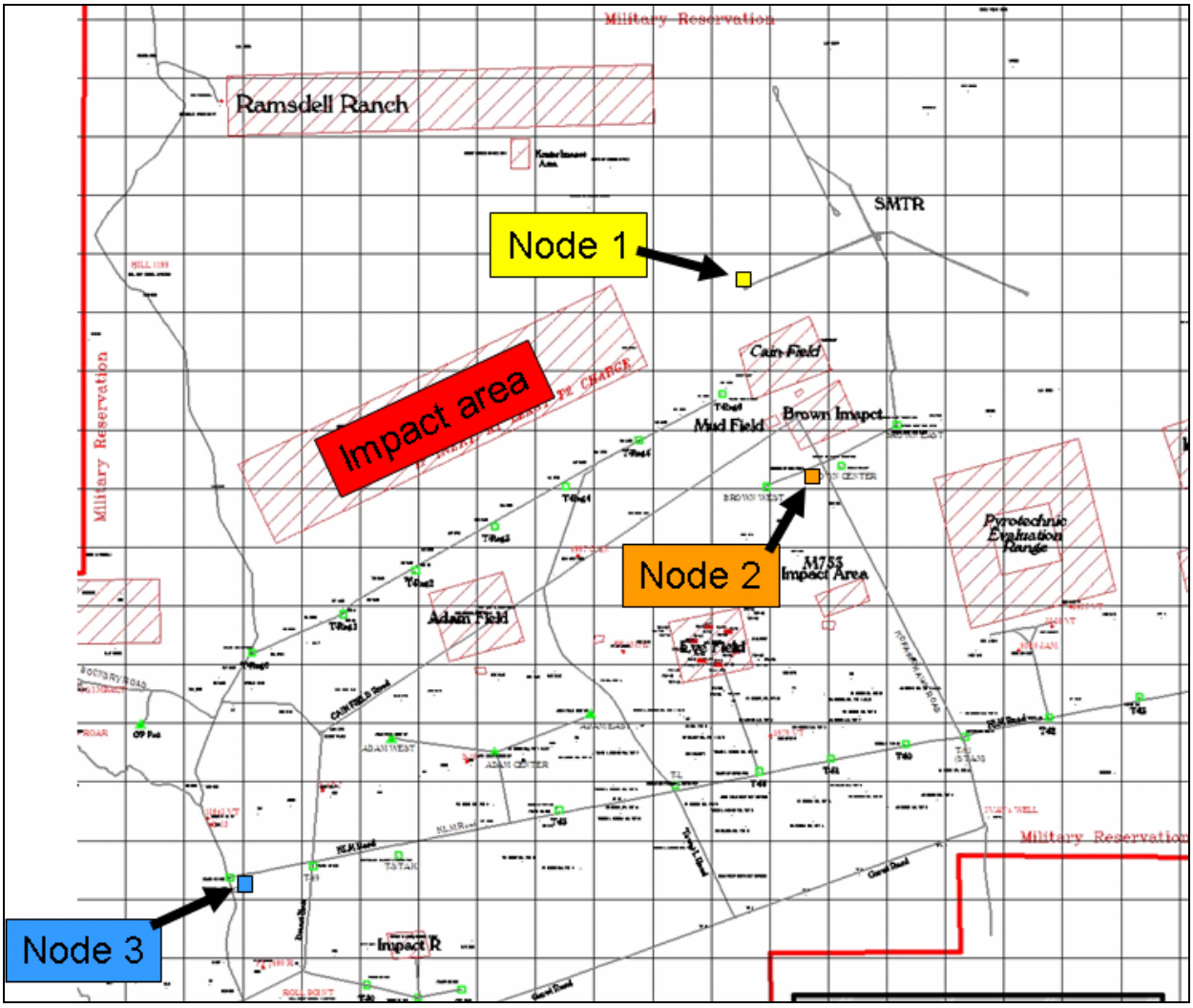


Figure 3. Detailed 1-km-grid map of the test area for week 2 (Fig. 1), depicting the impact area and the data collection points (nodes).

3 Firing Records

Ground truth, specifically firing records, is a critical component for establishing a monitoring capability on training ranges. Firing times put constraints on possible events and significantly reduce the amount of data analysis required for continuously recorded data. Further, records contain vital information concerning the types of ordnance used, which must be linked to analysis in order to have a high/low yield estimator and to prioritize cleanup efforts. A dedicated test was cost prohibitive, so our data collection does not have optimum ground truth as to firing times and sources. It does, however, provide a very realistic look at the complex and convoluted task of active range monitoring and also provides insight into wide-area monitoring versus impact-area-specific instrumentation of ranges.

Firing records for the March 2005 test were obtained for each day of data collection on a voluntary basis from range officers. These firing records provide the approximate number, type, firing times, and impact zones for the ordnance fired during the two-week period and are archived with the CRREL data set. Not all records were available, as some range officers did not disclose tests; thus there exists seismic acoustic signatures in our data set that are not accounted for in the ground truth.

4 Specifications of Sources Used in Measurements

The following sources generated the data that were recorded by our seismic and acoustic arrays. We have provided as much technical detail about each source as we could locate. Since these were "tests of opportunity," it was impossible to collect specific details about every source. Because of the close proximity of source and impact locations on training ranges, both muzzle blasts and ordnance impact/explosions are typically observed. The primary sources observed in the data set are attributed to mortar and artillery fire (Fig. 4 and 5). The artillery fire included both air-disbursed parachute munitions and high-explosive ground impact rounds.

Figure 4. Artillery used in this experiment.

Figure 5. Mortar launchers used in week 1.

Live fire sources

- M224 60-mm mortars
- M252 81-mm mortars
- M120 120-mm mortars
- M101A1 or M101 or M102 or M119A1 105-mm howitzers
- M114A2 or G-6 or M198 or M109A6 155-mm howitzers.

Calibration sources

Seismic: 10-gauge shot

Local geologic and environmental variables give each sensor installation unique response characteristics. To help define these and to validate local propagation models of the region, we record calibration "shots." These are impulsive, broadband sources at specified locations and times. This allows for analysis that infers accurate acoustic propagation, seismic attenuation, and seismic propagation speeds.

The calibration source contributes an important segment of data for use in understanding the seismic characteristics on the range. For this field data acquisition, we employed CRREL's custom-designed seismic and acoustic impulsive source generator, a 40-kg heavy-walled steel cylinder with a discharge chamber capable of firing a 10-gauge black-powder blank downward (Fig. 6). For range monitoring where receiver offsets exceed distances greater than 2 km, the 10-gauge thumper is not strong enough to provide a simultaneous calibration source for the entire range. It does, however, allow for both a reproducible seismic impulsive source and a consistent acoustic source that may be used in the validation of the local geology and seismic velocities up to a radius of 2 km around individual sensor nodes. The seismic calibrator was used during both weeks of data collection, providing a total of 49 ground truth events.

Figure 6. CRREL's 10-gauge seismic-acoustic impulse source ready for discharge on a YPG range road. It was determined that this source was not sufficiently large enough to be a robust ground truth source at ranges greater than 2 km.

Acoustic: propane cannon

While the emphasis of this research on range monitoring is on seismic sensing, acoustic data must not be ignored. For acoustic ground truth shots, we utilized a "Scare Away," model M4 from Reed-Joseph International M4 (Fig. 7), which produces single, 120-dB bangs that can be regulated from one bang every 30 seconds to one bang every 20 minutes. It uses a piezo ignition system, which operates without batteries or electricity and produces up to 200,000 ignitions. This propane cannon acoustic calibration source can be transported and discharged from a pickup truck, allowing for rapid data generation from a range of locations. The canon was used to generate 42 acoustic ground truth events for this two-week data collection.

Figure 7. Portable propane cannon used to generate acoustic waves. (This photograph was taken in New Hampshire.)

5 Sensors and Sensor Arrays

This section presents a description and images of the arrays of sensors used to record the seismic and acoustic signatures during the field tests.

The arrays of microphones and geophones were configured and placed at locations ranging from 3 to 7 km from the zone of impact. Triangular arrays of microphones and linear arrays of geophones were co-located at three positions (referred to as nodes in this report) during the weekly tests. Microphones co-located with geophones provide a means of instantly discriminating the mode of propagation for signals observed on a geophone. The data collected provide time-of-arrival (TOA) location capability and rough location information and help define the distance limitations of seismic monitoring for characterizing and assessing distributed-source ordnance-related compounds (ORCs). Singular sensor data provide information pertaining to detection and magnitude characterization.

The data acquisition systems consisted of three nodes that were developed at ERDC-CRREL. A typical node consisted of four 6-channel 24-bit digitizers, a recording system (in this instance a laptop computer), a GPS clock for recording the system time, a wireless network for remote control, 12 geophones, 12 microphones, and batteries (Fig. 8). Data were continuously

Figure 8. Node 3 site installation with met station at YPG during March 2005. Solar panels allow continuous operation at remote sites and enable optimal sensor placement without regard to hard power constraints.

recorded at a sample rate of one record per millisecond. For this data acquisition, only 4 of the 12 possible microphones were utilized.

The sensors used here were 4.5-Hz vertical and 1-Hz vertical seismometers and ½-inch free-field microphones (Fig. 9 and 10). The 1-Hz seismometers are Geospace HS-10-1 and are stamped on the side with the coil resistance, ~400 ohms. The HS-10 is a high-sensitivity, self-generating velocity

Figure 9. Geophones used for this field program: 1-Hz vertical-motion-sensing geophone with 0.1-V/mm/s sensitivity (center), and 4.5-Hz vertical-motion-sensing geophone with 0.03-V/mm/s sensitivity (orange on right).

Figure 10. Half-inch free-field microphone with windscreen. Its range is 3.15–20 Hz, and its sensitivity is 50 mV/Pa.

detector with extremely low natural frequencies. We utilized two of the 1-Hz sensors per node. The other approximately 10 seismic sensors were Geospace 4.5-Hz geophones. The microphones were Brüel & Kjær (B&K) 4165 and 4190 microphones at node 1 and GRAS 40 AF microphones at nodes 2 and 3. Both the B&Ks and GRAS sensors are ½-inch, externally polarized, free-field microphones with a sensitivity of 50 mV/Pa. The frequency range of the B&Ks is 3.5–20 kHz, and the GRAS microphones have a range of 3.15–20 kHz.

Linear seismic arrays were implemented to maximize the separation between the 1-Hz sensors in hopes of providing significantly distinct data points for analyzing the difference in time of arrival. The linear geophone arrays consisted of 12 sensors, with 1-Hz sensors at the ends and 4.5-Hz sensors placed in between. All geophones were equally spaced 15 m apart. The 4.5-Hz geophones were placed about 6 in. below the surface in the packed and gravel-laden, powdery ground and then buried (Fig. 11). The 1-Hz seismometers required a hole of approximately 10–12 in. and were also buried.

Figure 11. A 4.5-Hz geophone implanted in the fine soil beneath the surface gravel at YPG.

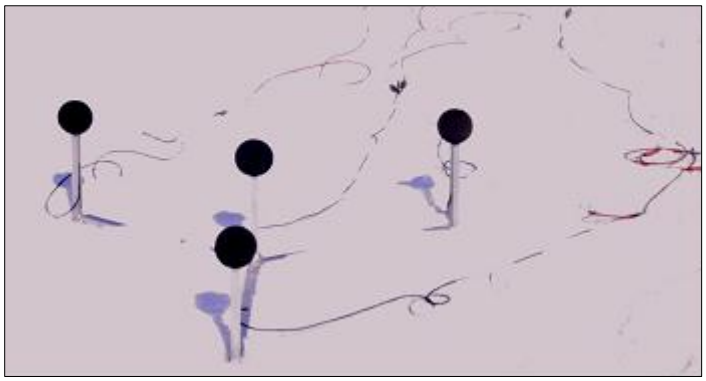


Figure 12. Layout of the 1-m acoustic sensor array.

The four microphones were placed 30 cm above the ground in the form of an equilateral triangle with 1-m sides (Fig. 12), with a microphone at every corner and one in the center. Along with the seismic and acoustic data, meteorological data were concurrently recorded to assist in interpreting the results.

The sensors were located in areas where we were able to access them for routine service without interfering with range firing operations. Closing roads and restricting access to portions of the range deemed within a line of fire or firing ellipse are standard safety practices on the YPG range. This rendered access to roads and regions directly adjacent to active impact regions untenable for our sensor locations. Thus, locations were chosen that afforded easy unrestrained access for routine instrument maintenance, system on/off control, and downloading of data and were not the closest possible sensor offsets. As a result, sensors were located a further 1–5 km from impact zones. The resulting sensor offset distances of 2–8 km from impact zones of interest presented additional challenges to detection and event association. It is, however, within the scope of this work to understand the applicability of monitoring remote ranges from large offsets and to consider the possibility of broad area monitoring applications.

During the first week (7–10 March 2005), sensor node 1 was placed just west of Bunker Amy, sensor node 2 was placed just east of gun position 12, and sensor node 3 was placed northeast of the Old Downrange Road intersection with Firing Front Road (Fig. 2).

For the second week of tests (15–18 March 2005), node 1 was located at grid location 3653600-m N/234700-m E, node 2 was placed just south of the Brown Road intersection with Tower M Road, and node 3 was placed adjacent to the southeast corner of Tower 49 (Fig. 3).

6 Environmental/Physical Site Characterization

Meteorological data

Meteorological data can drastically improve acoustic analysis performance by providing wind and temperature corrections to the sound speed. CRREL recorded meteorological data on seven temporary automated weather stations (AWSs), with each seismic/acoustic node having at least one AWS. The recorded meteorological variables include wind speed, direction, and air temperatures. Sampling intervals of 1 and 10 s were used for the meteorological data acquisition during these tests. Figure 13 depicts the CRREL meteorological data collected on March 17, 2005. CRREL meteorological data from all seven stations were archived for acoustic data analysis purposes. Daily YPG meteorological forecasts were also provided by the range officer and are archived with this data set.

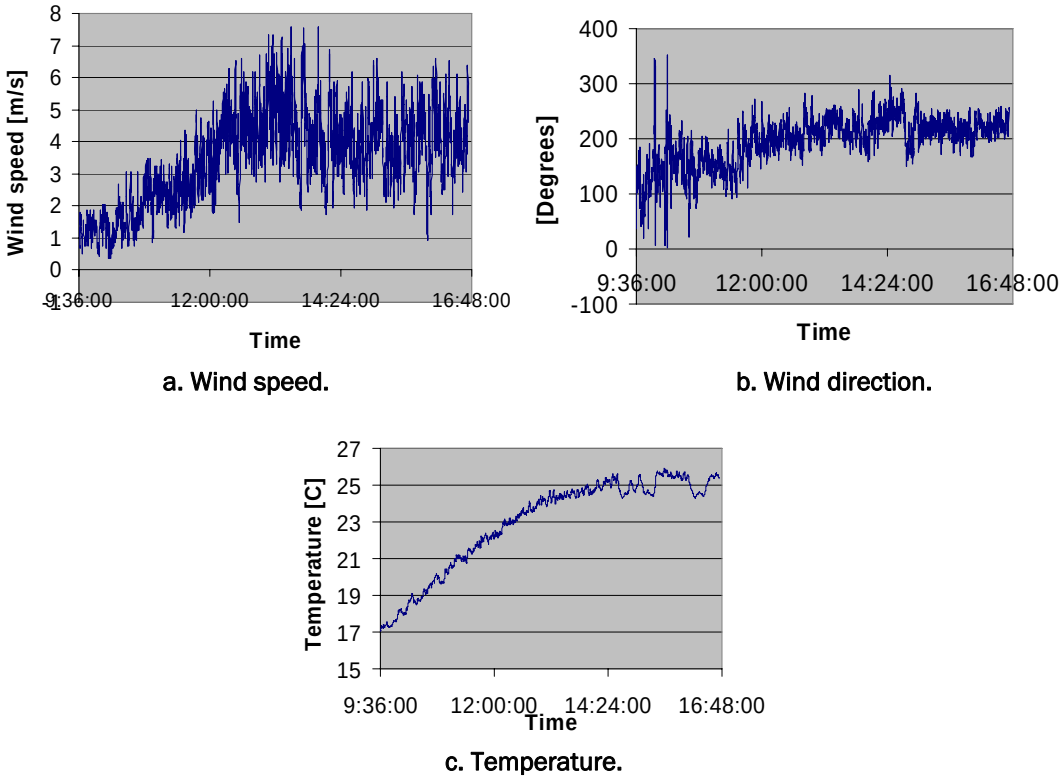


Figure 13. Meteorological data measured continuously at node 1 on 17 March 2005. This is representative of the meteorological data collected at the portable sites during this test. Data were collected at a rate of once every 10 s.

Geological site characteristics

Yuma Proving Ground is in the Sonoran Desert of the Basin and Range Province in southwestern Arizona (Millet and Barnett 1970). It is one of the hottest and driest areas in the nation. Larger than the state of Rhode Island, YPG encompasses more than 1,300 square miles. The ground surface within the observed impact zone is relatively flat, with 1- to 2-m-high ridges that meander generally north to south across the northern half of the site. Geological logs from borings near the center of the YPG Smart Weapons Test Range (SWTR) site suggest that the first 100 m of sediment are composed predominantly of silt, gravel, and sand. Sediment particles within the test area vary in size from gravel to clay, with locations in the site where sorting into distinct surface patches is evident. From 0 to 7 m deep, the materials are silt with sand and minor amounts of gravel. Between 7 and 28 m deep, the sediments are mostly gravel with some suggestions of boulders. From 28 to over 65 m deep, the sediments are predominantly silts and sands with minor amounts of gravel. The sensors were located in these alluvial sediments, and we assumed that the general layered velocity model for SWTR is a good approximation for the broader high-explosive impact area.

Seismic velocity studies on YPG yield compressional velocities on the order of 2 km/s. A portion of the SWTR subsurface on the KOFA artillery range had been characterized by the Kansas Geological Survey in a high-resolution seismic study down to a depth of 25 m (Miller et al. 2003). The compressional seismic speeds at the SWTR were resolved to 0.5 m using geostatistical methods. A pseudo inversion of seismic data acquired at SWTR has led to a three-layer velocity model for SWTR (Greenfield 2001) with a maximum compressional velocity of 2 km/s. The three-layered YPG velocity model is consistent with the Kansas Geological Survey study results. We have validated these velocity models by modeling both simple sources and moving vehicles (Anderson et al. 2002, 2003, Ketcham et al. 2003). In the current range monitoring effort, receiver offsets are up to 8 km, and the seismic wave speed is expected to be faster because the materials being sampled are deeper and stiffer than in the previous studies.

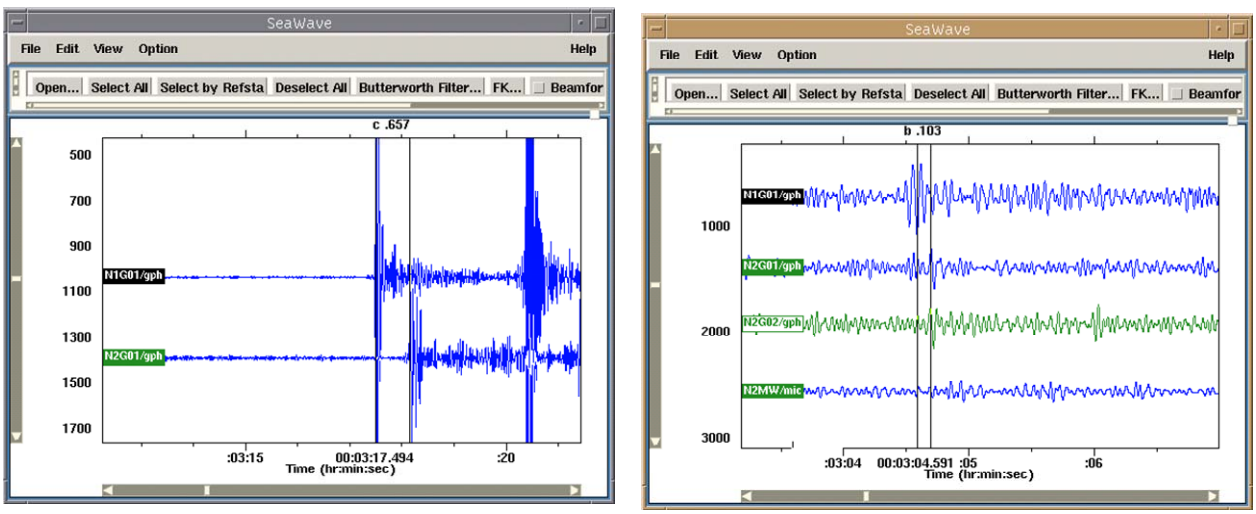
7 CSS/NDC Data Format

The National Data Center (NDC)/Center for Seismic Studies (CSS) data format used to store data on the CD-ROM is presented in this section. The format has its roots in the CSS approach that has been tested and improved over the last several decades. The heart of this format is the CSS 3.0 schema, a set of low-level tables and relationships that characterize seismic events. These core tables contain the ground truth event (seismic) catalog, seismic phase arrival information, magnitudes and supporting amplitudes, station, instrument, and array information, as well as a referential mechanism for accessing raw waveform data. By adopting this database and schema standard, we take advantage of the sophisticated processing, analysis, and reporting tools that already exist. This includes a web relational database and the capability for developing dynamic calibration and design and reporting of systems. While the existing schema doesn't necessarily address all information pertaining to local range monitoring, new schema table(s) may be developed to hold information relevant to range location data that do not currently exist. The purpose of schema design is to associate asynchronously received seismic and acoustic phase arrivals into a reliable catalog of seismic and acoustic events.

The core tables for waveform data are the *wfdisc*, *site*, and *sitechan* files and the *.w* data file. The *wfdisc* file lists the waveforms according to sensor and time. The *site* file documents individual sensor latitude, longitude, elevation, and date at the site (or node). The *sitechan* file logs the orientation of sensors. The *.w* file is a binary data file containing the waveforms. These tables and attributes are described in detail in the data archive for the test. Processing of the data, either manually or automatically, enables further populating of schema tables such as *event* and *orig* with event location, times, phase arrivals, amplitudes, etc.

8 Preliminary Seismic Velocity Study

A preliminary velocity study was conducted on seismic and acoustic arrivals for an event from week two during the YPG study. The purpose of this analysis was to estimate the local seismic velocity, understand the phases observed on the seismic trace, and gain an understanding of the maximum detection range for high-explosive ordnance. For this analysis, the seismic and acoustic arrivals at nodes 1 and 2 (Fig. 14) were evaluated to back-calculate the velocity of the compression wave arrival and to determine the distance between the impact and geophone 1 at node 1.



a. Difference of arrival times at node 1 (top trace) and node 2 (bottom trace) for the high-amplitude acoustic arrival observed on geophones.

b. Seismic P-phase arrivals from HE ordnance detonation plotted with microphone (bottom trace). Node 1 is the top trace, and two channels from node 2 are plotted for redundancy. The microphone (bottom trace) is plotted to verify that no acoustic energy is associated with this impact event.

Figure 14. Seismic and acoustic signatures from high-explosive (HE) impacts.

Obtaining the time difference between the large acoustic arrivals at nodes 1 and 2 in Figure 14a allows for the calculation of the relative distance from the event. In this example, the acoustic arrival dt = 0.657 s (without meteorological corrections). Using a typical acoustic wave velocity of 350 m/s yields:

$$\text{Distance} = dt \times V_{air} = (0.657\ \text{s}) \times (350\ \text{m/s}) = 230\ \text{m}. \quad (1)$$

Thus, node 1 is approximately 230 m closer to the event than node 2.

Evaluation of the seismic arrivals (note that the node 1 arrival is first) shows dt = 0.103 s, so the seismic velocity is a function of the distance calculated above and time, such that:

$$V_{seis} = \text{Distance}/dt = 230 \text{ m}/0.103 \text{ s} = 2{,}233 \text{ m/s}. \quad (2)$$

This agrees with the compression wave velocity (2,000 m/s) presented in the half-space depth portion of Greenfield's YPG three-layer model, given that the seismic waves travel deeper and faster at greater receiver offset distances.

The seismic velocity reported above and the time difference between the observed acoustic and seismic arrivals (Fig. 15) are used to calculate the distance from node 1 to the impact event.

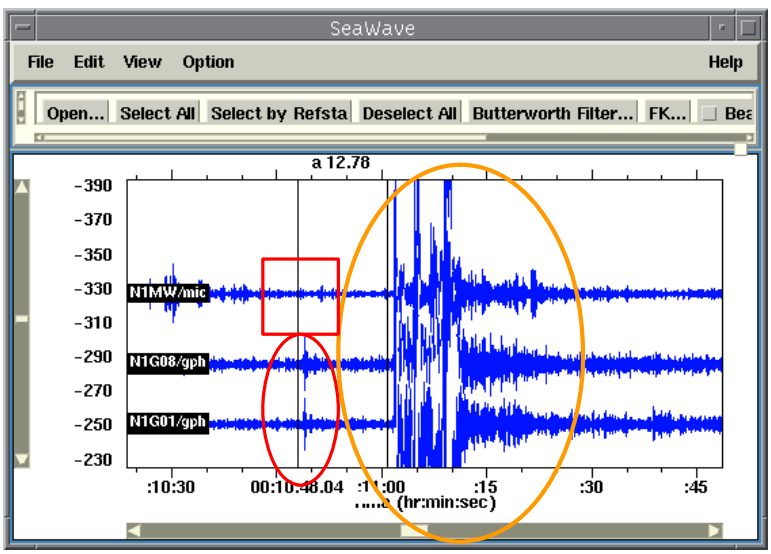


Figure 15. Node 1 microphone and geophone arrival data used to calculate time difference for waveform seismic and acoustic arrivals.

Thus, the distance between geophone 1 at node 1 and the impact event is determined according to:

$$T = (Distance/V_{seis}) - (Distance/V_{air}) = 12.78 \text{ s} \quad (3)$$

where V_{air} = 350 m/s (typical)

V_{seis} = 2,233 m/s (from above)

$Distance$ = abs[12.78/(1/2,233 m/s – 1/350m/s)] = 5,304 m.

Though the distances were not measured on the ground, scaled distances off YPG maps provide sufficient evidence to support this result. These initial findings support our theory that seismic P-wave arrivals from HE impacts will travel at high velocity (approximately 2,300 m/s) from 2 to 12 km. The accuracy of acoustic data can be improved by incorporating corrections for wind velocity. Seismic data from UXO impacts may be undetectable at distances in excess of 5.5 km because of their low energy source and path attenuation.

9 Example of Archived Seismic-Acoustic Data

In this section an example is presented of a segment of archived data for the purposes of understanding phase arrival using both seismic and acoustic data. The segments are typically three to five minutes long and consist of several events. Acoustic waves readily couple to surface seismic instruments and may introduce ambiguities in the seismic time series. By plotting the acoustic and the seismic traces together (Fig. 16), the acoustic arrival attributed to the detonation of the high explosive round is easily observed on both the acoustic and seismic trace. Recognizing the arrival as acoustic energy removes some of the ambiguity in determining if an arrival is a seismic or an acoustic phase in the seismic data and further presents a foundation for a velocity template to be developed and used in automated algorithms. The seismic compressional arrival phase (P) traveling at approximately 2.2 km/s should precede the much slower acoustic (~0.345 km/s) phase as shown in the prior section. Using the known acoustic arrival and the approximate acoustic location to gain rough distance, we can easily locate the seismic phase (Fig 17). Further, standard frequency-wave number (FK) array analysis indicates the approximate direction to the

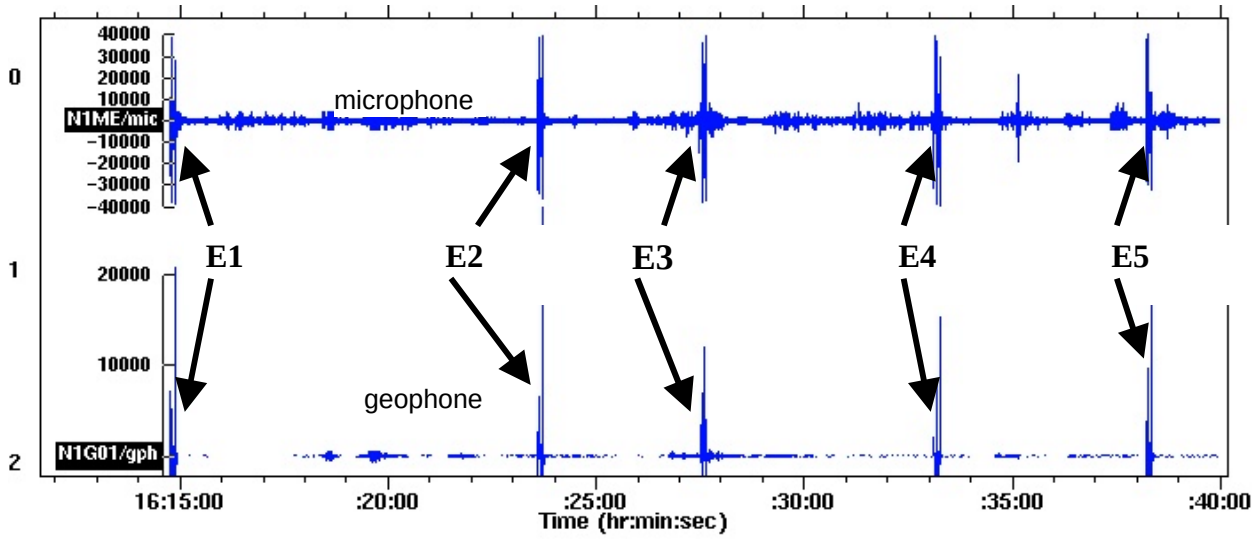


Figure 16. A 25-minute data file from March 17 showing five high explosive events observed on microphone (top trace) and seismic time series. The acoustic arrivals are evident from the extremely high signal-to-noise ratio and the same time of arrival on both seismic and acoustic traces. The seismic trace is not observable at this scale between HE acoustic arrivals, emphasizing the magnitude of the acoustic phase vs. the seismic phase.

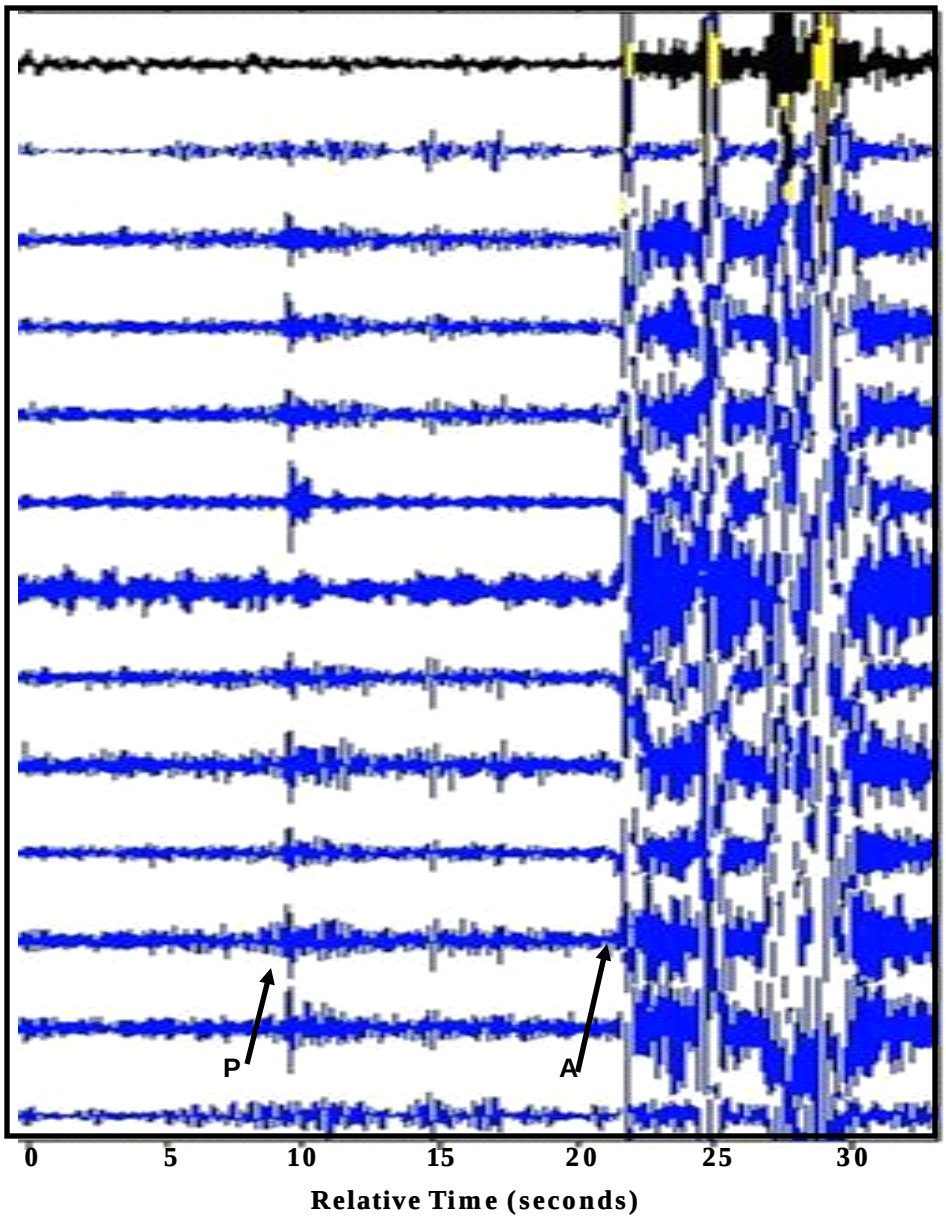


Figure 17. Magnified view of event 2 from plot 16. The record section illustrates a microphone (top trace) co-located with a linear array of 12 geophones. The seismic arrival (P) is observed at about 13 s prior to the amplitude saturated acoustic arrival (A). Note that the seismic phase is absent from the top microphone data trace. Traces 2, 7, and 12 are 1-Hz vertical sensors; the rest are 4.5-Hz vertical sensors.

origin of the arrival phase. This is an important method to implement, especially on busy multi-mission test ranges, where either seismic or acoustic arrays may reject signals when the indicated azimuth-to-source points to another active zone that is simultaneously active.

10 Conclusions

The March 2005 data collection experiment that was carried out in support of the active range monitoring project in the Distributed Sources focus area of the Environmental Quality program was a success on several levels. We observed excellent seismic signal-to-noise ratio for full detonations, demonstrating that seismic monitoring is a viable means for active range monitoring. Complex phase arrivals from both muzzle blast and impact detonation were observed, emphasizing the complexities associated with monitoring on range scales. Multi-mode sensors (seismic and acoustic) enable the discrimination between the true seismic and coupled acoustic arrivals observed in the seismic time series.

The data from this field experiment has a high level of integrity. It is archived in a modified CSS 3.0 format with robust meta data, so it is very portable data set lending itself to reproducible analyses. The preliminary velocity analysis agreed with prior YPG seismic studies and provides a necessary tool for validating phase arrivals in the observed data. The analysis of continuous data may be greatly reduced by incorporating firing templates to a time of interest. Local geologic velocities may be used to hone the templates using acoustic–seismic time difference of arrivals.

Data from this study are available by request to the authors.

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14. ABSTRACT

A seismic-acoustic field data acquisition experiment was conducted in March 2005 to support the ERDC Environmental Quality program, Distributed Source focus area. The Distributed Sources focus area strives to characterize the level of contamination in range environments attributed to ordnance residue for the purpose of range management and environmental remediation. This remote sensing research project emphasizes seismic magnitude measurements and subsequent inference of partial detonations and unexploded ordnance. The analysis of these data will help establish seismic-acoustic measurement criteria for remotely sensed seismic data to enable near-real time estimates of the seismic source characteristics of ordnance explosions, including level of detonation and location. We collected seismic and acoustic array data from Yuma Proving Ground from 7 to 18 March 2005. Three sensor nodes were set up over approximately 16-km^2 areas that encompassed partial or full impact regions. We employed both seismic and acoustic arrays with accompanying meteorological stations. The dual mode of acoustic and seismic monitoring is seen to have great benefit in discerning acoustic arrival from the seismically propagated energies. Acoustic arrivals that are attributed to ordnance detonation or muzzle blast are observed on both the seismic sensors and microphones with an extremely high signal-to-noise ratio. The experimental data acquisition of March 2005 provided a catalogue of waveforms that help to define the seismic and acoustic phase energy observed at several kilometers for sensor offset and a source scale of artillery ordnance magnitude.

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